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TRAC DEVELOPMENT AND ASSESSMENT STATUS*

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ABSTRACT

TRAC is being developed at the Los Alamos National Laboratory to provide an advanced systems code for light-water reactor accident analysis. The released TRAC versions (P1, P1A, and PD2) were intended primarily as benchmark codes for large-break loss-of-coolant accidents but PD2 has been applied successfully to TMI-type transients and other small-break transients. A fast-running version, PF1, is currently under development to address more efficiently and accurately these types of transients. All of the released versions have been subjected to testing against separate-effects, system-effects, and integral experiments covering a wide range of scales. Assessment results indicate that PD2 does a credible job overall; needed improvements are being addressed in PF1 and in modifications to PD2.

INTRODUCTION

The transient reactor analysis code (TRAC) is an advanced best-estimate computer program for the analysis of loss-of-coolant accidents (LOCAs) and other transients in light-water reactors (LWRs) and experimental thermal-hydraulic facilities. Pressurized water reactor (PWR) versions of TRAC are being developed, tested, and applied at the Los Alamos National Laboratory under the sponsorship of the United States Nuclear Regulatory Commission (NRC). The TRAC development project began in April 1975 and the first documented version (P1)[1] was completed in December 1977. An improved version (P1A)[2] was released through the National Energy Software Center (NESC) in March 1979. Reports containing detailed results of P1A developmental and independent assessment analyses have been published.[3,4] The first production version (PD2)[5] was released to the NESC in October 1980. Major improvements in PD2 are in the areas of reflood heat transfer, mass conservation, numerics, and constitutive relations. Developmental assessment results for PD2 are summarized in Ref. 6 and reported fully in Ref. 7.

The original objective for TRAC was to provide a unified benchmark systems code for large-break LOCAs validated by extensive testing against experiments. As a benchmark code, running time was not a primary concern for these relatively short transients. However, TRAC has become a production code for which running time is important. This trend was accelerated following the Three Mile Island (TMI) accident and the change of emphasis to small-break LOCAs and other long transients. Although not specifically designed or optimized for these types of transients, PD2 has been used successfully

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to analyze the TMI accident, small-break LOCAs in the loss-of-fluid test (LOFT) facility, and loss-of-feedwater scenarios in full-scale PWRs. The fast-running version (PF1) currently under development is designed to address these transients more efficiently and accurately.

Our approach in developing TRAC has been to use mechanistic models where feasible, provide geometric detail where needed, and use state-of-the-art two-phase thermal-hydraulic models and numerical methods. We have included as much physics as possible to minimize scaling problems. The TRAC user is not required to select code models and correlations for each application but basically only specifies the problem geometry and boundary conditions. The code determines flow and heat-transfer regimes and supplies appropriate interfacial and wall interaction terms. Since the code is being tested against a wide variety of experiments involving a large range of scales, this approach places a great burden on the constitutive relations. From the beginning our approach was also to make TRAC as versatile and flexible as possible. It can be applied to problems ranging from simple pipe blowdowns to four-loop PWR transients. Its modular features made it possible to use the Los Alamos PWR version in the development of a boiling-water reactor (BWR) version (TRAC-BD1) at the Idaho National Engineering Laboratory (INEL) and the COBRA/TRAC program at the Battelle-Pacific Northwest Laboratory (PNL). We believe that the approach adopted for TRAC development has the greatest prospects of leading to a predictive capability for full-scale reactors and new experimental configurations.

In addition to the major code releases, several other important accomplishments are worthy of note. The first consistent, continuous, and complete calculation[8] of all phases of a large-break LOCA was performed with TRAC in early 1978 for a full-scale, four-loop PWR. This calculation showed that the peak clad temperature (PCT) was reached during the blowdown phase rather than the reflood phase. Recent LOFT and Semiscale experiments have confirmed this result. The first TRAC pretest prediction[9] was performed for LOFT test L2-2 in December 1978. An early core flow reversal which caused rewetting of the entire core was not calculated in the pretest prediction. When the actual initial conditions were used in the posttest analysis,[10] very good agreement was obtained with the entire system response except for the peak power (hot) rod. The pretest prediction for the next LOFT test (L2-3) was in almost exact agreement with the measured PCT.[11] Another major accomplishment is the successful application of TRAC to the TMI accident in October 1979.[12] This was the first application of TRAC to a small-break LOCA. Using letdown flows within uncertainty limits, agreement was obtained with known system conditions out to about 3 h into the accident.

TRAC DEVELOPMENT

Detailed PWR Version (PD2)

A summary description of the most recently released TRAC version (PD2) is given in this section. Detailed descriptions can be found in the user's manual[5] and in Refs. 13-17. Most of the features described here are common to all the released versions. PD2 improvements are mainly in the areas of reflood heat transfer, solution strategy, numerics, constitutive relations, and mass conservation.

A three-dimensional cylindrical or two-dimensional Cartesian hydrodynamic calculation can be performed within the vessel component. Components outside the vessel are treated in one-dimensional geometry. The vessel module is used to model all regions inside the pressure vessel including the downcomer, lower plenum, core, upper plenum, and upper head.

Two-phase flow is treated using nonhomogeneous, nonequilibrium models. A two-fluid six-equation model is used within the vessel component. These equations are based on the conservation of mass, momentum, and energy for the separate liquid and vapor fields. Supplementing these field equations are constitutive relations (or closure equations) that specify (1) the transfer of mass, energy, and momentum between the liquid and vapor phases and (2) the interaction of these phases with the system structure. The nature of these interfacial transfers and interactions is dependent on flow topology and, therefore, a flow-regime-dependent constitutive equation package is included.

The flow in the one-dimensional loop components is described by a five-equation drift-flux model. These equations are based on conservation of mass, energy, and momentum for the mixture and conservation of mass and energy for the vapor. Liquid and vapor velocities are expressed in terms of a relative velocity (drift) that is dependent on flow topology.

Heat transfer models in TRAC include (1) conduction models to calculate temperature fields in structural materials and fuel rods and (2) convection and boiling models to provide heat transfer between structure and coolant. A generalized boiling curve is constructed from a library of heat transfer correlations based on local surface and fluid conditions. This is an area in which significant improvements were made between P1A and PD2.

Conduction models are available for obtaining temperature fields in one-dimensional (cylindrical) pipe walls, lumped-parameter slabs in the vessel, and two-dimensional (cylindrical) fuel rod geometries. The fuel rod conduction analysis accounts for gap width and conductivity changes, metal-water reactions, and quenching phenomena. A fine-mesh axial renoding capability is available for fuel rods to allow more detailed modeling of reflood heat transfer and tracking of quench fronts. Quench front motion is determined explicitly from a two-dimensional (r-z) conduction solution in the rods using super-fine axial noding determined dynamically by a fine-mesh rezoning method. This is the most significant model improvement over P1A, which uses an empirical velocity correlation for the quench front.

The system of field and constitutive equations is solved using efficient spatial finite-difference techniques. A semi-implicit time differencing technique is normally used in most components. This technique is subject to the Courant stability limitation that restricts the time-step size in regions of high-speed flow. A fully implicit time differencing option is available for the fluid dynamics in the one-dimensional components. This option allows fine spatial resolution in regions of high velocity (e.g., in a nozzle) without restricting the time-step size.

Application of P1A to long transients revealed a problem in numerical mass conservation. This problem was eliminated in PD2 mainly through changes in the drift correlations and improvements in the vessel solution strategy including (1) direct matrix inversion (as opposed to iteration) for vessels having less than 80 cells, (2) a coarse-mesh rebalance technique for vessels having more than 80 cells, (3) relinearization of the vessel equations to correct donor celling when the fluid velocity changes sign during a time step, and (4) installation of a backup procedure when invalid temperatures, pressures, or void fractions are encountered. PD2 is also improved in the area of detection and prevention of "water packing" problems.[17] As a result of these improvements and correction of errors found in P1A, PD2 is a much more reliable and smoother running code.

TRAC is completely modular by component and by function. Component modules, which consist of sets of subroutines, are available to model vessels (with associated internals), steam generators, pressurizers, etc. The user can construct a wide variety of configurations by joining together an arbitrary number of these components in a meaningful way. Thus, the user can solve problems ranging from a simple pipe blowdown to a multiloop PWR LOCA. Component modularity allows component models to be improved, modified, or added without disturbing the rest of the code. Functional modules are available for multidimensional two-fluid hydrodynamics, one-dimensional drift-flux hydrodynamics, thermodynamic and transport properties, wall heat transfer, etc. Functional modularity allows the code to be easily upgraded as improved correlations become available.

TRAC can be used to obtain steady-state solutions to provide self-consistent initial conditions for subsequent transient calculations. An important characteristic is the ability to address the entire LOCA (blowdown, bypass, refill, and reflood) in one continuous and consistent calculation. Trips can be specified to simulate protective system actions or operational procedures (e.g., the opening or closing of a valve).

TRAC is designed to run on a CDC 7600 computer, but standard programming techniques are used to ease its conversion to other computers. All storage arrays are dynamically allocated so that the only limit on problem size is the available core memory.

Fast-Running Version (PF1)

TRAC-PF1 is the next major version being developed at Los Alamos. A preliminary version of PF1 is currently being tested; an assessed and documented version is scheduled for release late this summer. PF1 will treat small-break LOCAs accurately and efficiently (real time or better) using a two-fluid one-dimensional representation while at the same time retaining the three-dimensional vessel option for large-break analysis.

PF1 uses a one-dimensional two-fluid hydrodynamics package that replaces the one-dimensional drift-flux formulation in PD2. This capability is in use not only at Los Alamos but also in the BWR version (BD1) at INEL. A stability-enhancing two-step numerical method[18] has been implemented in the prototype PF1 code. This method removes the Courant time-step limit and allows TMI-type transients to run at real time or better. In conjunction with this, the wall heat transfer is treated more implicitly to enhance stability. A one-dimensional core component has been developed for PF1. It consists basically of a fuel rod inside a pipe component and includes a reflood heat-transfer model.

A critical flow model to treat flows at breaks has been implemented and is being tested. Programming has been included for a noncondensable gas field but associated modifications to the constitutive package have not yet been completed. The capability to handle stratified flow in horizontal pipes is available and is being tested. A reactivity feedback model is available based on average fuel, moderator, and void coefficients. Improved trips and plant controls are under development to allow better simulation of operational transients. Most of the features described below will also be included in PF1.

PD2/MOD1

Additional capabilities and improved models have been implemented in PD2 since that code version was released. These improvements are being used in-house to study TMI-type transients. A reactivity feedback model as described above has been implemented and tested in PD2. A delayed nucleation model has also been implemented and is being tested. A multimaterial distributed-slab model is undergoing testing in PD2. This model performs a one-dimensional conduction calculation in vessel heat slabs and is much more accurate than the lumped-parameter model in the released version of PD2. A double-ended pressurizer is available that allows attachment of a valve or other component at the top. An improved valve model is also available that allows opening or closing at specified rates based on upstream pressure.

TRAC ASSESSMENT

Code testing activities at Los Alamos include both developmental and independent assessment. Developmental assessment proceeds concurrently with and is closely coupled to code development; it involves testing against existing data and its purpose is to help guide development of the current code version. Independent assessment is performed with a released and documented code version; its purpose is to test predictive capability, i.e., to determine how well the code performs when the test results are not known in advance. In addition to the assessment activities, we are applying TRAC to full-scale PWR transients in support of a multinational research program on refill and reflood in large-scale facilities, a multifault accident study involving severe accident sequence analysis, and resolution of safety issues of interest to the NRC.

Developmental Assessment

Experimental tests selected for the developmental assessment of PD2 are listed in Table I. This set includes most of the experiments used for P1A developmental assessment plus additional integral, systems, and heat-transfer tests. The assessment set includes separate effects (tests involving basically only one plant component and one LOCA phase), system effects (coupled components up to entire loops but only one LOCA phase), and integral effects (system tests covering more than one LOCA phase) over a wide range of scales. Results indicate that PD2 does a credible job overall for all of these tests.[6,7] Improvements over P1A are mostly in the reflood

TABLE I

TRAC-PD2 DEVELOPMENTAL ASSESSMENT EXPERIMENTS

No.	Experiment	Scale	Thermal-Hydraulics Effects
1	Edwards Horizontal Pipe Blowdown (Standard Problem 1)	1/100[a]	One-dimensional separate effects during blowdown including critical flow, flashing, slip, and wall friction.
2	CISE Unheated Vertical Pipe Blowdown (Test 4)	1/1200[a]	Same as 1 plus pipe-wall heat transfer, flow area changes, and gravitational effects.
3	CISE Heated Vertical Pipe Blowdown (Test R)	1/1200[a]	Same as 2 plus critical heat flux (CHF).
4	Marviken Vessel Blowdown-Long Nozzle (Test 4)	1/1[b]	Same as 1 plus full-scale effects and delayed nucleation effects.
5	Marviken Vessel Blowdown-Short Nozzle (Test 24)	1/1[b]	Same as 4 plus nonequilibrium, two-dimensional nozzle flow.
6	THTF Blowdown Heat-Transfer Test 177	1/1[c]	Separate effects during blowdown including rod heat transfer with dryout and rewet.
7	Creare Downcomer tests (3) - Low ECC Subcooling	1/15[d]	Two-dimensional separate effects during refill including countercurrent flow, interfacial drag, and downcomer penetration.
8	Creare Downcomer tests (3) - High ECC Subcooling	1/15[d]	Same as 7 plus condensation effects.
9	FLECHT Forced Flooding Tests (PWR Tests 4831 and 17201, SEASET Test 4)	1/1[e]	One-dimensional separate effects during reflood including heat transfer, quench-front propagation, liquid entrainment, and carryover.
10	Bennett Vertical Tube CHF (Tests 5336, 5431, and 5442)	1/1[f]	One-dimensional pipe-wall steady-state heat transfer over the entire range of the boiling curve.
11	Semiscale Heated Blowdown Test S-02-8	1/2000[g]	Synergistic and systems effects during blowdown in a multiloop PWR simulator.
12	Semiscale Integral LOCA Test S-06-3	1/2000[g]	Integral effects during a complete LOCA in a multiloop PWR simulator.
13	Nonnuclear LOFT Blowdown (Test L1-4)	1/60[g]	Integral effects during isothermal blowdown and refill in a PWR simulator (nuclear core not in place).
14	Nuclear LOFT Integral LOCA (Test L2-2)	1/60[g]	Integral effects during a large-break LOCA in a scaled PWR.
15	CCTF Reflood Test C1-1	1/1[h]	Multidimensional and system effects during refill and reflood.

[a]Scale given is based on pipe flow area.

[b]Scale based on vessel and break pipe dimensions.

[c]Full-scale 7x7 array of electrically heated rods.

[d]Linear downcomer dimensions.

[e]Single bundle of ~ 100 electrically heated full-scale rods.

[f]Full-scale compared to fuel rod dimensions -- flow inside the tube is nonprototypic.

[g]Power and volume scaling.

[h]Full-height components; radius of electrically heated core is 1/5 scale.

heat-transfer area where a more sophisticated and mechanistic model was implemented. As a result of this and numerous other improvements in solution strategy, numerics, and constitutive relations, PD2 is much more reliable and smoother-running than P1A. Running time is the same or improved over P1A even though the reflood heat-transfer treatment is more complex.

To illustrate the performance of PD2, we have selected an integral test (S-06-3) in the Semiscale facility and an integral test (L2-2) in the LOFT facility. Test S-06-3 was a large-break LOCA test with accumulator and high- and low-pressure injection into the intact loop cold leg.[19] There is good agreement between the calculated and measured mass flow rates on the vessel side of the break (Fig. 1). In the intact loop, TRAC predicts the rapid decrease in mass flow rate due to two-phase degradation in the pump. As shown in Fig. 2, TRAC tended to somewhat underpredict the PCT but the overall comparisons were good except for the high-power rods at the top of the core.

Test L2-2, the first nuclear-powered test in the LOFT facility, was a large-break LOCA from an initial power of 25 MWt and an intact hot-leg temperature of 580 K. The LOFT nuclear core contains 1300 fuel rods which are full-scale in the radial dimension and approximately half-scale in length. The calculated hydraulic response generally agrees very well with the data[20]. The primary discrepancy is a lower accumulator discharge rate in the calculation which delays refilling of the lower plenum. However, the core refill is predicted reasonably well and the PCT is close to the observed value. Figure 3 compares the break flow (vessel side of break) and shows good agreement except for the initial period of subcooled critical flow (first 10 s). The underprediction during the first 10 s is probably due to not calculating delayed nucleation properly.

Figure 4 shows typical results for the cladding temperature response at the core midplane for the central fuel bundle (high-power zone). The data shown are from three neighboring thermocouples. Other thermocouples in this same fuel bundle and at the same elevation show significantly different behavior so that the spread in the measurements is much larger than that shown in the figure. The TRAC-PD2 results shown are typical for all the rods in the central power zone except that the rods adjacent to the broken hot leg do not experience the second dryout (this was also observed in some of the measurements). Both the calculation and data show a series of dryouts and rewets with the peak clad temperature occurring during blowdown. Comparisons at other elevations and in the intermediate- and low-power zones are similar to those shown in Fig. 4.

Independent Assessment

Independent assessment of TRAC-PD2 is currently under way at Los Alamos and other national laboratories. The principal test facilities being used at Los Alamos for this activity are listed in Table II. These facilities span a wide range of scales and types. Most of our efforts in this area involve small-break and operational transients in LOFT and Semiscale.

Thus far PD2 pretest predictions have been made for LOFT small-break tests L3-2, L3-7, L3-5, and L3-6. Posttest analyses of tests L3-1 and L3-7 have been completed and similar analyses are in

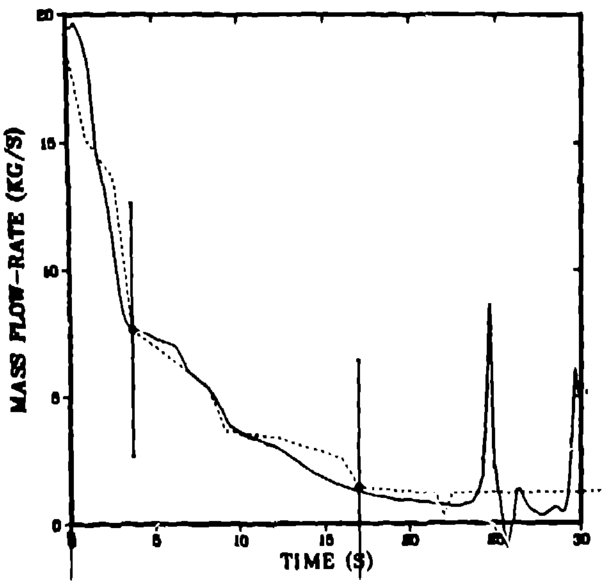

Fig. 1. Break flow (vessel side) for Semiscale LOCA test S-06-3 (solid = PD2, dash = data).

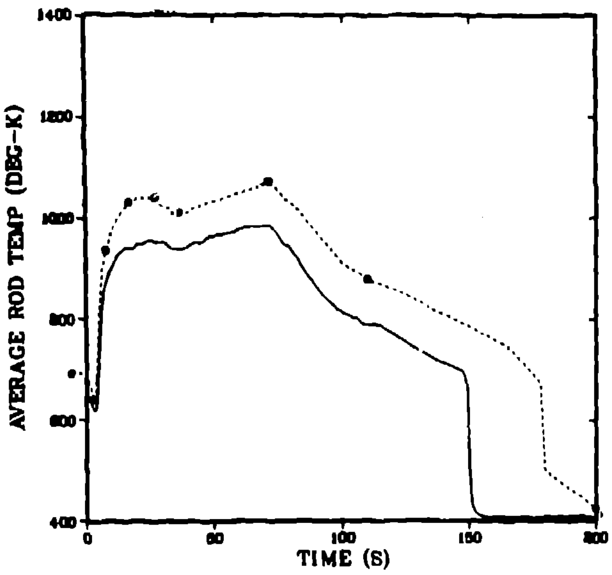

Fig. 2. PCT for Semiscale LOCA test S-06-3 (solid = PD2, dash = data).

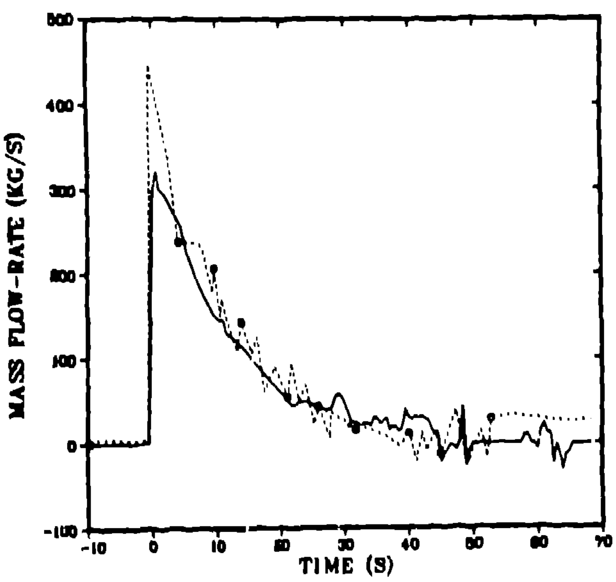

Fig. 3. Break flow (vessel side) for LOFT LOCA test L2-2 (solid = PD2, dash = data).

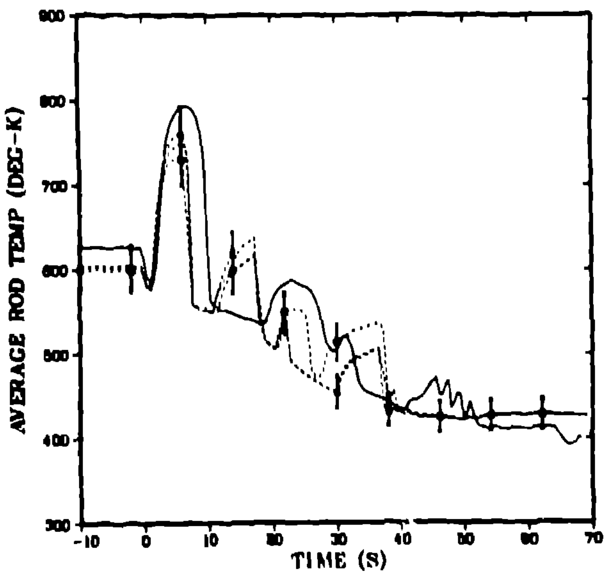

Fig. 4. PCT for LOFT LOCA test L2-2 (solid = PD2, dash = data).

TABLE II

FACILITIES[a] FOR TRAC INDEPENDENT ASSESSMENT AT LOS ALAMOS

Facility	Location	Scale	Description
Semiscale Mod-3	INEL	Small	Integral LOCA facility with full-height core, two active coolant loops, external downcomer, and upper-head-injection capability.
LOBI	Ispra, Italy	Small	Blowdown/refill system with two active coolant loops and full-height simulation of a PWR.
FLECHT-SEASET	Westinghouse	Small	Separate- and systems-effects reflood facility with a single-bundle full-height core and one external loop.
THTG	ORNL	Small	Separate effects pressurized-water loop with single-bundle full-height core.
NRU	Canada	Small	Reflood test section inside an operating nuclear reactor; test section contains one 6x6 bundle of full-height fuel rods.
LOFT	INEL	Intermediate	Integral LOCA test facility with nuclear core and two coolant loops.
PKL	FRG	Intermediate	Full-height, refill/reflood facility with 340-rod core, three coolant loops, and external downcomer.
Downcomer Tests	Creare and BCL	Intermediate	Separate-effects facilities for refill phase of LOCA.
Marviken III	Sweden	Large	Separate-effects facility for critical flow.

[a]All facilities are electrically heated unless specified otherwise.

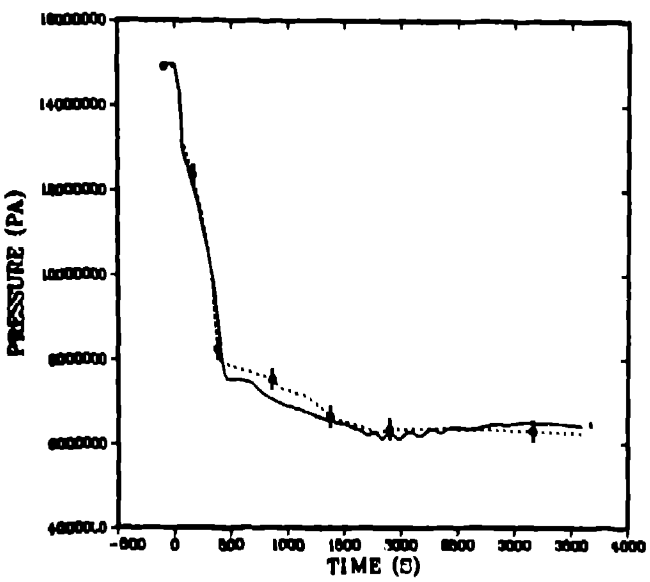

Fig. 5. Primary system pressure for LOFT small-break test L3-7 (solid = PD2, dash = data).

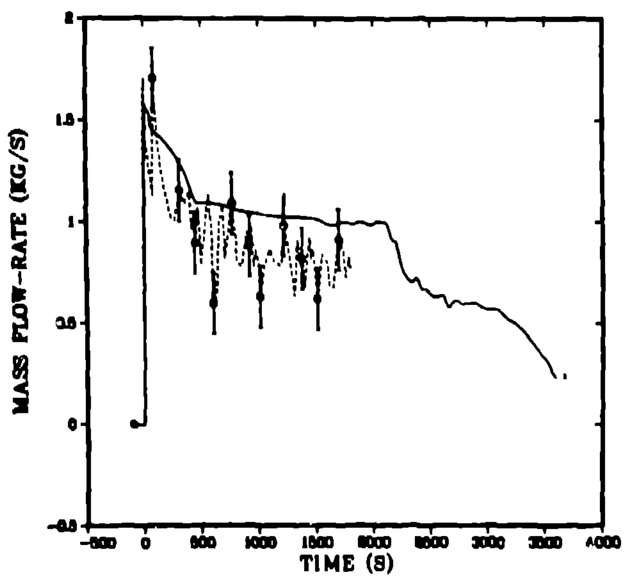

Fig. 6. Break flow for LOFT small-break test L3-7 (solid = PD2 dash = data).

progress for L3-5 and L3-6. Both pretest predictions and posttest analyses will be performed for operational transients L6-1, L6-2, and L6-3. The pretest predictions for L3-1 and L3-7 showed that accurate modeling of the secondary system and the break flow is much more important for small breaks than for large breaks. Posttest calculations[21] for these two tests show generally good agreement with the data. This is illustrated by Figs. 5 and 6 which show, respectively, the pressure and break flow comparisons for test L3-7.[22] No mass conservation problems were encountered in this calculation which extended over more than 1 h of transient time. However, these calculations have shown that a more accurate treatment of critical flow in very small breaks is needed.

Posttest, blind predictions[23] for FLECHT-SEASET reflood tests 31701 and 31805 (US Standard Problem 9) were made with a preliminary version of PD2. Data from these tests are not yet available for comparison with the calculations. Steam generator tests in this facility are also scheduled to be analyzed with PD2. Five Marviken calculations were completed and are currently being documented. A PD2 posttest calculation of PKL reflood test K9 (International Standard Problem 10) was completed.[24] PD2 correctly predicts most of the test features but does not predict the early quench at the top of the core. Semiscale tests currently being analyzed with PD2 include small-break test S-07-10D and pumps on/off tests S-SB-P1, S-SB-P2, S-SB-P7, S-SB-P3, and S-SB-P4. A pretest prediction of S-07-10D with P1A yielded the most accurate results of all participants.[25]

SUMMARY AND CONCLUSIONS

TRAC was initially intended as a carefully assessed benchmark code capable of running entire (blowdown, refill, and reflood) large-break LOCAs. It is now evolving into a multipurpose best-estimate production code capable of handling small-break LOCAs and other long transients under a unified code system. Version PD2 does a good job on large-break LOCAs and will also handle small-break LOCAs and operational transients. Results thus far indicate that the basic modeling and numerical framework in TRAC is fundamentally sound. Model improvements have been identified and these improvements have been or will be incorporated into the next versions (PF1 and PD2 mods).

A conclusion to be drawn from our experience is that it is feasible to develop a code that can predict a broad range of experiments without the use of "code dials" that can be adjusted from one experiment to another. We believe this is an essential element in establishing predictive capability for situations where direct experimental data does not exist (e.g., an actual reactor under accident conditions). TRAC-PD2 and PF1 represent significant technical progress toward such a code.

ACKNOWLEDGMENT

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